

THE USE OF MULTIPLE OXYGEN IMPLANTS FOR FABRICATION OF BIPOLAR SILICON-ON-INSULATOR INTEGRATED CIRCUITS*

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ABSTRACT

This paper describes the radiation improvements obtained by fabricating bipolar integrated circuits on oxygen-implanted silicon-on-insulator substrates which were manufactured with multiple (low-dose) implants. Bipolar 74ALS00 gates fabricated on these substrates showed an improvement in total dose and dose-rate radiation response over identical circuits fabricated in bulk silicon.

INTRODUCTION

Silicon-on-insulator substrates offer a significant advantage for bipolar technology. By replacing the parasitic collector-substrate junction with an insulator, several radiation failure mechanisms (involving the substrate) are eliminated. First, the insulator "interrupts" leakage current paths beneath trench isolation and recessed field oxide structures. This solves a major total dose problem for most commercial bulk designs. Second, replacing the collector-substrate junction with an insulator eliminates it as the primary source of photocurrent collection in both SEU and dose-rate environments. Finally, an insulating substrate guarantees latchup immunity because it interrupts all substrate (pnpn) paths between adjacent components.

For the past 30 years, single-poly dielectric isolation has proven itself to be an excellent insulating substrate technology for bipolar. More recently [1,2], CMOS memory devices were fabricated on oxygen-implanted SIMOX (Separation by IMplantation of OXYgen) starting wafers. These early CMOS experiments proved that SIMOX substrates were manufacturable and could provide an alternative approach to conventional dielectric isolation.

Since that time, all attempts to fabricate bipolar transistors on similar wafers have failed. Threading dislocations and stacking faults in the 3-4 micron epitaxial layer grown on these substrates resulted in defect densities above $1E8$ defects/cm². Bipolar transistors fabricated on these substrates exhibited excessive collector-emitter leakage currents. When compared to bulk wafers at 3-10 defects/cm², SIMOX technology was unacceptable for bipolar circuit fabrication.

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This paper demonstrates the first application of a technique for reducing defects in SIMOX material by over four orders of magnitude [3,4]. To accomplish this, oxygen was simply implanted into a silicon wafer using multiple doses instead of the traditional single dose. Furnace annealing was performed after each implant. Two n-type epitaxial layers were then grown over the remaining "seed" silicon before standard bipolar processing was resumed.

Wafers using both single- and multiple-dose implants were incorporated into a production lot of Texas Instruments IMPACT-X (1.5 μ m) Advanced Low-power Schottky process technology devices. By inserting SIMOX substrates into a bulk (trench-isolated) process, a fully oxide-isolated SIMOX/trench structure was obtained (figures 1 and 2). Quad 2-Input 74ALS00 NAND gates (figure 3) and test transistor structures were fabricated and compared to identical devices manufactured on bulk silicon.

The results of this research demonstrated that bipolar devices, fabricated on multiple-implant SIMOX substrates, can compete with conventional dielectric isolation for many radiation-hardened system applications.

SIMOX WAFER PREPARATION

In order to establish a relationship between dislocation densities and oxygen implant dose for SIMOX substrates, bulk wafers were implanted with 150 KeV oxygen (at 560°C) to doses as high as $2.25E18$ ions/cm². Some wafers received all of their dose in a single implant. Others were processed using several low-dose implants, each followed by a 16-hour thermal anneal at 1275°C, to achieve an equivalent total dose. Sample substrates were examined after each implant/anneal cycle using a Transmission Electron Microscope (TEM) to look for material dislocations.

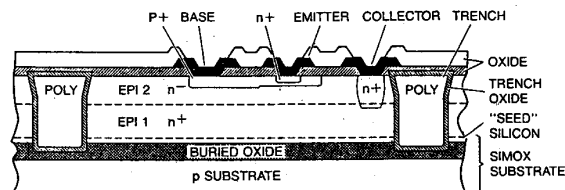
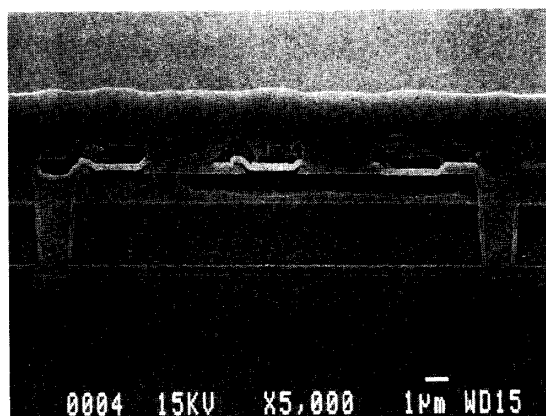


FIGURE 1. CROSS-SECTIONAL DRAWING OF FULLY-OXIDE-ISOLATED SIMOX/TRENCH STRUCTURE FABRICATED ON A SIMOX SUBSTRATE



SEM PHOTOGRAPH OF DEVICE

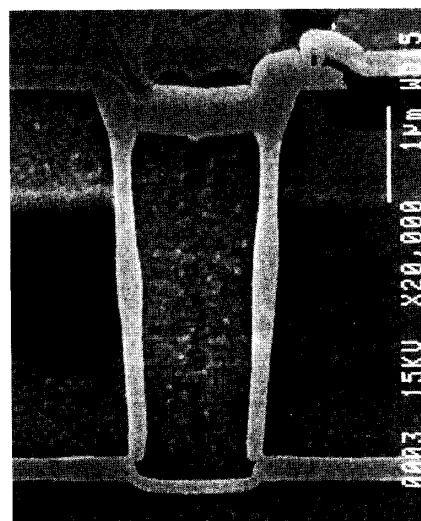
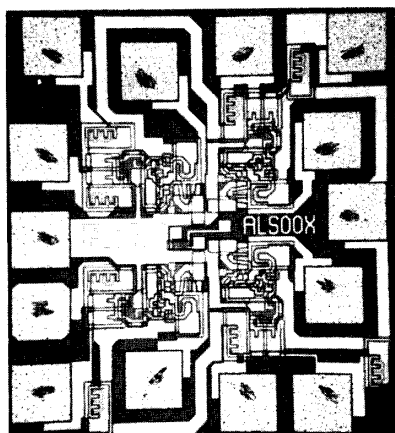
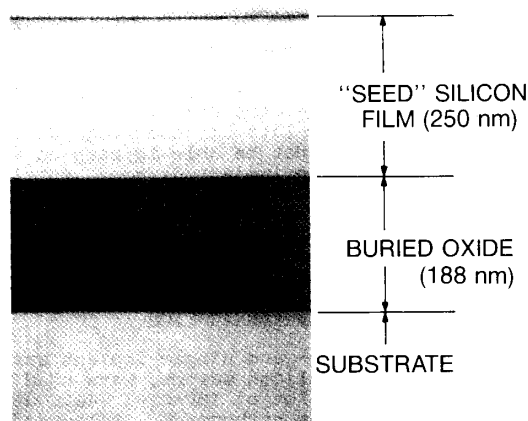
SEM PHOTOGRAPH OF SIMOX
OXIDE/TRENCH INTERFACEFIGURE 2. CROSS SECTION OF 1.5 μm IMPACT TECHNOLOGY
DEVICE FABRICATED ON A SIMOX SUBSTRATEFIGURE 3. DIE PHOTOGRAPH OF TEXAS INSTRUMENTS
74ALS00 QUAD 2-INPUT NAND GATE
FABRICATED ON A SIMOX SUBSTRATEFIGURE 4. TEM PHOTOGRAPH OF MULTIPLE-IMPLANT
SIMOX SUBSTRATE

Figure 4 shows a cross-sectional TEM photograph of a SIMOX substrate after three multiple (low-dose) implant/anneal cycles. The surprising fact is that no oxygen precipitates were found in the buried oxide layer, and no dislocations were seen in the remaining "seed" silicon film. It can be seen from the photograph that oxygen ions have penetrated approximately 250 nm into the starting silicon substrate and have formed a continuous 188 nm layer of buried oxide. In contrast, TEM examination of single-implant wafers, which received an equivalent total dose in one cycle, found many oxygen precipitates through-

out the buried oxide layer and tiny "web-like" threading dislocations in the seed film.

A complete understanding of physical phenomena causing this improvement in defect density is not available. One theory is that oxygen precipitates (in the buried oxide) serve as a source of stress in the lattice from which dislocations can form. Our experimental matrix of implants found a threshold oxygen dose where precipitates did not form. Performing multiple implants, keeping each one below this threshold dose, proved to be critical for fabrication of defect-free substrates.

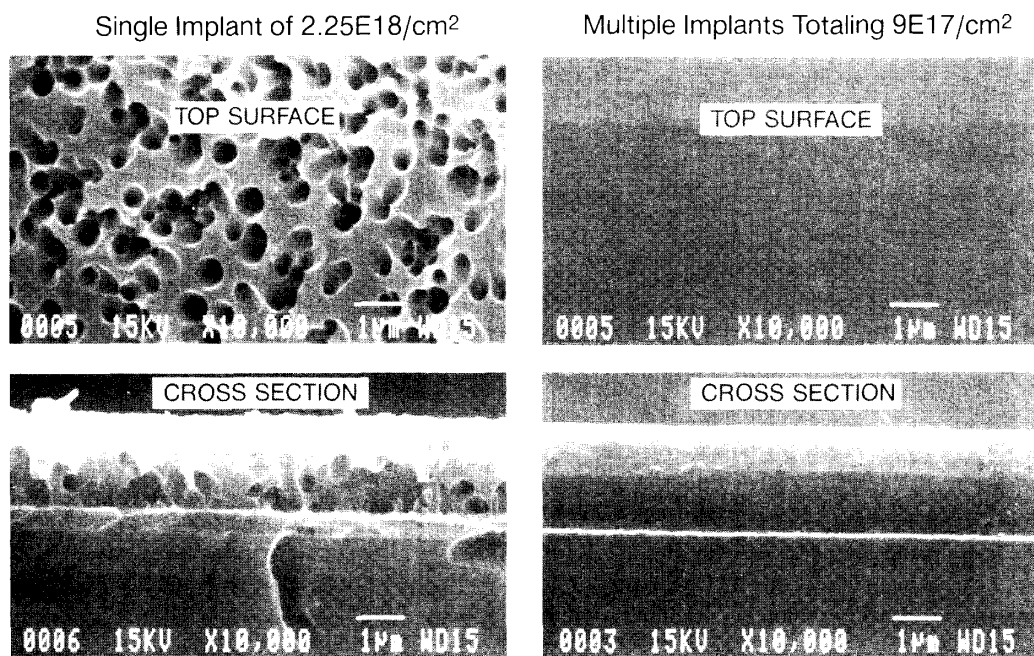


FIGURE 5. SEM PHOTOGRAPHS OF SECCO ETCHED SIMOX SUBSTRATES AFTER 2.5 μm OF EPI GROWTH

The physical mechanism for precipitate formation may not be entirely "dose dependent" as explained above. Another mechanism [4], referred to as an "implant-rate dependent" effect must also be considered. It is postulated that silicon lattice annealing (during implantation) may not be able to keep up with the ever-increasing implant damage. Portions of the lattice may not be able to recover fast enough, allowing for large oxygen precipitates to form. If this is true, experiments at even higher implant temperatures must be considered.

DEVICE FABRICATION

Both multiple- and single-implant wafers, along with bulk silicon wafers, were used to fabricate a split lot of IMPACT-X 74ALS00 NAND gates and test structures. Selected substrates from each implant/anneal variation were processed along with standard bulk material. Two n-type epitaxial layers were grown to a depth of 4 μm . These epi layers eventually form the transistor's active collector and buried collector regions. The normal reactive ion etched trench isolation process was slightly modified to accommodate for the depth/structure of the buried SIMOX layer.

Sample substrates were analyzed after epi growth with preferential SECCO etching [5] and examined with a Scanning Electron Microscope (SEM). Figure 5 compares traditional SIMOX material prepared using a single implant to that prepared using three (low-dose) implants. Note the dramatic difference between single-implant and multiple-implant material. When multiple-implant techniques are used, large (mm^2) areas of the wafer appeared to be

defect-free. On wafers prepared with the best multiple-implant material, defect densities were estimated to be about $1\text{E}3/\text{cm}^2$ by using standard SEM examination.

ELECTRICAL CHARACTERIZATION

Electrical testing revealed acceptable yields (greater than 30% at wafer probe) from multiple-implant SIMOX wafers receiving total oxygen doses between $9\text{E}17$ and $1.8\text{E}18$ ions/ cm^2 . No yield was obtained on wafers receiving an equivalent single dose. Transistors from all single-dose wafers exhibited extremely high (mA level) collector-emitter leakage currents, consistent with the high defect density measurements made previously.

Since the experimental lot showed both functional and DC parametric yield on bulk and multiple-implant SIMOX wafers, direct electrical comparisons were performed. Pre-rad test data (upper pair of traces in figure 6) shows typical transistor gain characteristics for the 2 x 6-micron emitter test structures. Note the excellent agreement between bulk and multiple-implant SIMOX devices. Electrical test data from 74ALS00 gates showed almost no discernible differences between bulk and multiple-implant SIMOX switching times or DC parametric measurements.

In summary, fabricating IMPACT-X technology devices on multiple-implant SIMOX substrates did not affect their electrical performance. Devices fabricated on single-implant wafers exhibited extremely high collector-emitter leakage currents and no functional circuit yield.

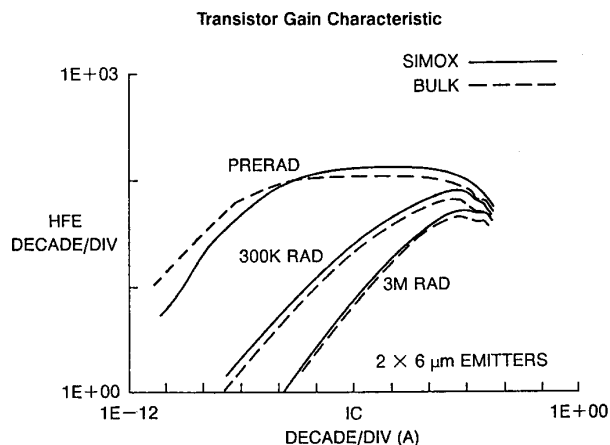


FIGURE 6. COMPARISON OF RADIATION PERFORMANCE OF MULTIPLE-IMPLANT BULK TRANSISTORS (Radiation bias conditions were $V_{ce}=2V$ and $V_{be}=0V$.)

RADIATION TEST RESULTS

All total dose testing was performed in Cobalt 60 at dose rates of approximately 100 Rad(Si)/sec. Both bulk and multiple-implant test transistors and circuits were exposed to a total dose of 3 MRad(Si). Time between sequential irradiations was kept to less than five minutes.

Comparison of transistor gain characteristics at increasing doses (figure 6) shows very similar degradation of bulk and SIMOX devices. From an analysis of these curves, gain degradation (in both devices) at low injection appears to be due to increased surface recombination at the interface where the base-emitter depletion region reaches the insulating oxide over the junction. Building devices on SIMOX substrates should not (and did not) affect any characteristics of this surface oxide.

In contrast to the excellent correlation obtained between bulk and SIMOX transistors during total dose testing, 74ALS00 NAND gate devices showed differences between bulk and SIMOX. Bulk devices failed to operate at all doses beyond 300 KRad(Si). Multiple-implant SIMOX devices showed no failures past 3 MRad(Si). Figure 7 compares propagation delay time versus dose for bulk and SIMOX NAND gates. As shown in the figure, SIMOX operation was maintained to 3 MRad(Si) where the test was halted.

Analysis of bulk device failures uncovered the reason why SIMOX gates performed so well. Under ionizing radiation, leakage currents were found to form between adjacent trench-isolated transistors. Total dose testing of trench isolated structures from a process monitor chip confirmed this fact. It is postulated that hole trapping in the "oxide liner" surrounding the trench is responsible for inverting the p-type substrate under the trench. In fact, a similar total dose response was encountered on bulk trench devices from two other manufacturers [6]. The under-the-trench leakage path is eliminated on SIMOX

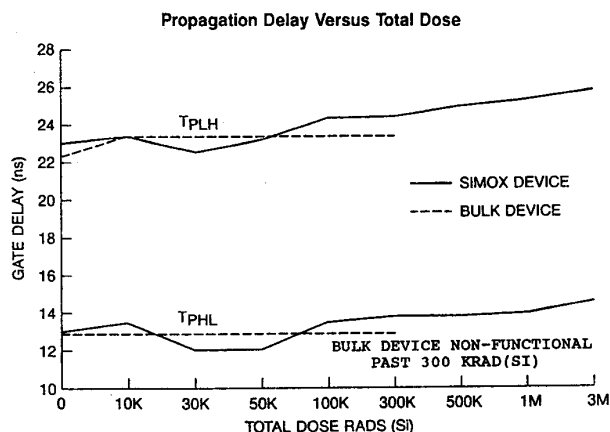


FIGURE 7. COMPARISON OF RADIATION PERFORMANCE OF MULTIPLE-IMPLANT SIMOX AND BULK 74ALS00 NAND GATES

structures, as each transistor is completely surrounded by oxide.

Dose-rate testing was performed at the White Sands Missile Range LINAC using electron pulses of 30-nsec width. Test results on bulk 74ALS00 gates showed dose-rate upset thresholds at 1E9 Rad(Si)/sec. By comparison, multiple-implant SIMOX gates did not exhibit upset until 5E9 Rad(Si)/sec. This five times improvement in dose-rate tolerance for SIMOX is attributed to the fact that a buried-oxide structure eliminates the bottom of the collector-substrate junction, a major source of photocurrent in bipolar structures. Further improvements can be obtained if photocurrent compensation techniques (used in conventional dielectrically-isolated circuits) are added to the design.

CONCLUSIONS

Multiple (low-dose) implant/anneal techniques were found to significantly reduce the defect densities in SIMOX substrates. When wafers were implanted with a series of doses (each below a threshold dose) and annealed after each implant, defect densities of approximately 1E3/cm² were achieved.

Advanced Low-power Schottky integrated circuits were demonstrated on these wafers with electrical characteristics equivalent to bulk. Bipolar SIMOX 74ALS00 gates showed an enhanced radiation tolerance over identical devices fabricated on bulk silicon. SIMOX devices demonstrated full specification performance past 3 MRad(Si) with dose-rate upset thresholds at 5E9 Rad(Si)/sec.

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